RADIOWAVE PROPAGATION - THE BASIS OF RADIOCOMMUNICATION

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1. INTRODUCTION

Radiowave propagation, progressively studied and understood during the past 100 years, has been exploited to provide an ever-growing range of radiocommunication services. The nature of propagation, which often provides only a variable and distorted representation of the transmitted signal at the receiver, presents both the opportunity to use radio systems and the challenge to design systems which have the means of combating the imperfections. This challenge, of processing weak and fluctuating signals so as to obtain the best possible information flow, has led to the development of the electronics industry,

In common with other papers at this Conference, it will be impossible to give a fair assessment of all the advances in the understanding of propagation which have taken place. This survey can only be a personal selection of highlights; this particularly applies to the more recent work where a comparatively large number of eminent research workers have made, and continue to make, major contributions. Recent work is reflected in the series of proceedings of the IEE Antennas and Propagation Conferences, as well as in other major Conferences; in papers presented to the General Assemblies of International Union of Radio Science, URSI; in the Recommendations of the International Telecommunication Union, Radiocommuniction Sector, ITU-R, previously the CCIR; and in specialised technical periodicals, etc.

My choice has been to try to give more or less equal weight, chronologically - so ignoring the much greater effort devoted in recent years - and to name only some of the researchers of earlier generations. Sources are not referenced directly, but a very limited bibliography is appended.

2. THE FIRST 30 YEARS

The laboratory demonstrations of the existence of electromagnetic waves with radio wavelengths by Hertz in 1887-8 built upon the research into electromagnetism in the first half of the nineteenth century by Faraday and others, and upon the theoretical work of Maxwell in the 1860s and 70s. Hertz demonstrated reflection and refraction and measured the wavelength and velocity of the radiation.

Developments in technology were, however, required before this laboratory curiosity could be turned to practical use. In 1894 Lodge demonstrated a radio system using a coherer as detector, which opened the way for Marconi to put radio to practical application. Receiver sensitivity and reliability were greatly improved by the invention and development of other detectors, and later by the start of the era of electronics with the diode and the 'audion' amplifying triode. In the 1890s the main tuning element in the circuitry was the antenna, and Marconi, by progressively increasing the size of his antennas, was able to progressively extend the communication range by exploiting the better ground wave propagation characteristics of lower frequencies.

Even so, theory and experiment suggested that radio communication was limited to a range of 200-300 km until Marconi tried to communicate across the Atlantic. Marconi's success led to a proposed revision of diffraction theory in order to account for the result; fortunately this was quickly refuted by Lord Rayleigh. It also led to the suggestion, independently by Heaviside and Kennelly, of an ionised reflecting layer in the upper atmosphere.

Such a layer had been surmised by Balfour Stewart in 1882, but even in 1926, after the direct experimental verification of the layer's existence, it could still be described during discussion at an IEE meeting as an 'academic myth'.

The first accurate propagation measurements were made by Duddell and Taylor in 1905. They measured the currents in the receiving and transmitting antennas at 2.5 MHz with ranges between 30 km and 1.9 km. Subsequent work, such as that by Austin and Cohen, concentrated on lower frequencies, in line with communication usage. The first world war stimulated a rapid growth in radio communication and the development of radio direction-finding. The 1920s also saw the start of domestic broadcasting at MF, with a growing need to determine antenna efficiency and coverage area.

In the early 1920s a number of people, both amateur and professional, began to find that short wavelengths, above 3 MHz, yielded extraordinarily strong signals over great distances. In 1924, following a proposal from the Marconi Company, the VLF Empire Communications System, then being implemented, was abandoned and a contract for an HF beam system was placed. In view of the performance requirements and the very limited understanding of HF propagation, this was an extremely adventurous step. The Radio Research Station was set up at Slough in 1920, and there also in 1924 Appleton and Barnett measured the height of the ionosphere; such a measurement was also made at about the same time by Breit and Tuve.

In 1919 the International Union of Radio Science (URSI) was formed, as a successor to the International Commission of Scientific Radio Telegraphy, and played a prominent part, as it continues to do, in the coordination of propagation research and information exchange. In 1927 the International Radio Consultative Committee (CCIR) was set up by the International Telecommunication Union to provide technical information, including propagation methods, for the design, planning and operation of radio services.

3. THE 1930s

In 1931 regular measurements of the ionosphere began at Slough. The techniques used there were applied in 1935 to the first demonstration of radar. In 1929 Eckersley and Tremellen described an ionospheric prediction method at a conference in Tokyo. Prediction techniques improved during the 1930s as more measurements became available and as the effects of the solar cycle, the earth's magnetic field, and geomagnetic storms were understood. The magneto-ionic theory was developed by Hartree, Appleton, Booker and others. During the second International Polar Year, 1932-3, a British expedition to Tromso, Norway, extended ionospheric studies to high latitudes.

At the same time interest was being turned to the application of 'ultra-short wavelengths'. Marconi's first tests, using frequencies just above 30 MHz, were made in 1928. In the early 1930s, Uda in Japan and Marconi in Italy both used trans-horizon systems at 600 MHz, while systems operating across the English channel were installed by Clavier and Gallant at 1500 MHz, and by McPherson and Ullrich at 17 GHz. In 1932 an experimental broadcasting transmitter at 39 MHz was established in London. Blumlein's choice of 45 MHz for the first high-definition television system took into account both the capabilities of contemporary technology and the available propagation information. Theoretical studies of the effects of diffraction around the earth were undertaken by Van der Pol and Bremmer, while Eckersley, Millington and Norton examined the effect of refraction in the earth's atmosphere and methods of treatment by 'modifying' the effective earth curvature.

A significant milestone is the report of the Committee on Radio Wave Propagation of the CCIR, prepared at the London meeting in November 1937. This report included:

- ground wave propagation curves for frequencies between 150 kHz and 5 MHz for both sea water and average land;

- sky wave curves for frequencies between 150 kHz and 1.5 MHz;

- examples of ionospheric field strength contours for different times and seasons at 8.6 and 18.8 MHz and of the variation of maximum usable frequency with distance;

- field strength curves taking account of diffraction around the curved earth, including curves for the height-gain obtained by raising the antennas, for frequencies between 30 and 150 MHz.

4. THE 1940s

The second world war saw a further dramatic surge in interest in propagation. HF communication was the mainstay over long distances; prediction techniques continued to improve and the different approaches developed in the UK, USA, Germany, etc., can still be detected in the methods currently in use. The first ionospheric storm-warning forecasting service was set up at Great Baddow. There were major advances in the understanding and use of VHF and microwaves, notably for radar. Solar noise, first noticed by Jansky in 1932, was seen more often on the UHF equipments, beginning the study of radio astronomy.

After the war the IEE held a number of Conventions and meetings which recorded the major developments of the war years. The 1947 Convention on Radiocommunications included major papers by Appleton and by Tremellen and Cox, together with a summary by Smith-Rose of the work of the Radio Research Station. This summary covers not only the research activities at HF and LF but also introduces radio-meteorology - in particular, the effect of refractive index changes, of hydrometeors and of gaseous absorption at millimetre wavelengths.

The variable structure of the troposphere was studied by a number of researchers in the 1930s, e.g. Hull. But the developments in World War II provided a major stimulus to tropospheric research. Despite some remarkable examples, in the Winter of 1939-40, metre-wave propagation beyond the horizon using CHL radar, and of a 1.5m radar in Bombay 'seeing' the African coast 2000 km away, it was centimetric radar which dominated research for many years. Several war-time reports in the UK and USA drew attention to the key role of the vertical structure of the radio refractive index; extreme variations of which produce the phenomenon of 'ducting' studied theoretically by Booker. These and other related studies were brought together under the heading of 'radio meteorology', in which the n-structure and its variability in space and time were key factors. The war-time work and immediate implications were subsequently published in a volume of the M.I.T. series (1956) and in a joint Physical Society/Royal Meteorological Society Report (1947). These studies also included an evaluation of absorption and scattering of microwaves by tropospheric media; work in which Ryde in the UK and Van Vleck in the USA were prominent. Radar meteorology grew out of this work accompanied by the increasing use of radio-sondes on a world-wide basis for probing tropospheric structure.

5. THE 1950s

The 1950s were perhaps the peak period of the use of HF for long-distance fixed-service communications. Ionospheric studies also reached a peak during the International Geophysical Year, 1957-58, when the Royal Society Expedition to the Antarctic made a contribution to the understanding of propagation in the southern auroral region. The decade also saw the expansion of VHF television and sound broadcasting and the beginning of effective civil land mobile radio. These uses require propagation information for low antenna heights and for the effects of terrain and buildings.

There were extensive field strength surveys and measurement campaigns to determine the coverage and behaviour of VHF and UHF radio systems. VHF ionospheric scatter and UHF tropospheric scatter systems provided means for communicating where intermediate relays were impossible, but the mechanism for tropospheric scatter propagation was debated extensively.

A special issue of Proc IRE was devoted to tropospheric scatter in 1955. For some time, theoretical work fell into two alternative approaches; one based on a model of scatter from isotropic turbulence, the other assuming some form of partial reflection from stratified layers of large, local gradient in the vertical structure of the refraction index. The view was not clarified until the development of radio refractometers and high-power radars enabled detailed probing of n-structure to be carried out. Joint use of these techniques was initiated in the UK and subsequently exploited by other countries.

As a part of the IGY activities, the first space research satellites were launched. Since then, space research has led to a fundamentally new understanding of the ionosphere and the magnetosphere. This, in conjunction with the power of computers, has resulted in new and complex models of the ionosphere and in sophisticated prediction methods.

6. THE RECENT PAST

The development of space technology has enabled communication satellites, along with undersea cables and fibres, to take much of the growing demand for long distance communication. For satellite communications the refraction, attenuation, scatter and scintillation occurring on earth-space paths has been studied.

Mobile and television services have been introduced at UHF where diffraction losses, scatter from buildings, etc., and attenuation due to vegetation become more important. The remarkable and successful use of 900 and 1800 MHz for hand-portable radio telephone services would have been thought quite ridiculous only a few years ago. At UHF and SHF there is substantial frequency sharing, most notably between terrestrial and space services, and the precision of propagation predictions used in the coordination of service planning has a significant impact on the cost of the installations. An example of a current major research facility is the dual-polarisation rain radar at Chilbolton. Systems are now in use at millimetric wavelengths, stimulated by both the very wide bandwidths, and the attraction of controllable coverage and extensive frequency re-use in the absorption bands, although still hampered somewhat by the technology available.

The incessant demand for increased communications in the past 50 years has continued to require more detailed and accurate propagation information, extending to higher frequencies and concentrating particularly on the statistics of variation with time and location. The introduction of modern digital systems has required a re-appraisal of propagation information with a need to place emphasis on the measurement and prediction of the dispersion of a signal, as well as its amplitude, to yield the channel transfer function. Extensive frequency re-use has resulted in interference-limited performance in many parts of the spectrum, and propagation predictions are used in system design and in assessing system performance and reliability.

7. PROPAGATION STUDIES ACROSS THE SPECTRUM

7.1 Low and medium frequencies

The first LF prediction formula of Austin and Cohen was re-examined as further measurements were made in succeeding years, clarifying the pattern of day-night variations. The voyage around-the-world by Round, Eckersley, Tremellen and Lunnon, and the observations of interference between surface and sky-waves by Hollingworth, gave a clearer view, with an estimate of the height of the ionosphere and an explanation of the asymmetry between westward and eastward propagation in terms of the motions of electrons in the earth's magnetic field.

Surface wave propagation around the earth was studied by Sommerfeld, Van der Pol, Bremmer and Norton, more recently the refraction due to the atmosphere has also been properly included. Millington's empirical method for determining the effect of mixed land/sea paths has been vindicated by theory and experiment, and a method for determining ground wave propagation through high-rise city areas has been developed.

The lower ionosphere has been modelled in detail and VLF and LF propagation within the earth-ionosphere waveguide can be predicted by ray-path or waveguide methods, aided by the computer power now available. The presence of the low conductivity dielectric in the Greenland ice cap within the waveguide yields interesting results.

In contrast MF sky-wave studies have been adopted an an empirical approach, based upon the performance of practical broadcasting transmitters on the imperfect earth. The effect of the near horizontal magnetic field at low latitudes on vertically polarised signals is included. Studies are continuing on longitudinal differences in propagation characteristics.

7.2 HF ionospheric propagation

Using the practical results from high frequency ionospheric circuits, Eckersley and Tremellen were able, within a few years, to produce world-wide prediction 'shadow charts' based on the position of the sun. Chapman's theoretical work led to improved models. Martyn, Millington, Newburn Smith, Appleton and Beynon considered the relationship between vertical and oblique incidence propagation.

The increasing resource of ionospheric observations permitted the first ionospheric mapping to be done, and there was a great improvement in maps during the war years. The longitude effect and the equatorial anomaly were discovered in both Japan and the UK.

Ionospheric data now archived in the World Data Centres has been used to construct numerical maps which take account of ionospheric dynamics and the effect of the earth's magnetic field to interpolate between observatories. Predictions of signal absorption are based upon studies of magneto-ionic theory.

Long term studies and predictions are usually based on monthly median observations, but the substantial day to day variations in the ionosphere limit the prediction accuracy. Studies of solar-terrestrial physics, with observations from space vehicles and from ground-based projects such as Eiscat, are improving the understanding of short-term variability.

Modifications to the ionosphere, caused by powerful transmissions, were first noticed as cross-modulation - the Luxembourg effect. Now deliberate ionospheric heating is employed to facilitate experiments of the physical effects.

Sporadic-E ionisation affects propagation both at HF and VHF, but its occurrence and strength of reflected or scattered signals can still only be indicated in statistical terms. Ionisation due to meteors is used for VHF burst-mode communications.

7.3 Propagation at frequencies above about 30 MHz

At the higher frequencies where the ionosphere has only a minor effect; propagation is affected by diffraction, scatter, refraction in the troposphere and by the attenuation of atmospheric gases. Modern communications require propagation information not only between well placed antennas, but also into and within buildings and for antennas on moving vehicles and in obstructed locations. Propagation studies above 30 MHz have a shorter history, somewhat more than half of the 100 years, but the communications potential of the vastly wider bandwidth at higher frequencies is such that most propagation research is directed there. Because of this, an overall review of progress in propagation studies should concentrate on the higher frequencies, but this has not been done here due to the historical context of this Conference.

Diffraction over irregular terrain has been studied both for discrete paths and, statistically, for categories of environment. For obstructed paths, important for land mobile communications and broadcasting, the signal variability near buildings and losses due to vegetation have been studied. These effects, combined with the ground profile, determine the coverage of a system and the dispersion, which is now so important for digital modulation. Point-to-point communications utilise carefully chosen antenna locations, but scatter from prominent features and the shielding obtained from terrain or buildings are important.

When considering frequency sharing, and the two extremes of the probability distribution for signal intensity, tropospheric scatter and ducting in atmospheric structures with non-standard refractive index profiles must also be taken into account.

A new era of tropospheric work opened in October 1957, with the Russian 'Sputnik' and - a few months later - with the US satellite Explorer 1. There are now many communication satellites in orbit, and planning for their performance (especially as regards mutual interference between various services - space and terrestrial) is a major problem for the engineer. Scattering and absorption by rain, snow and ice in the atmosphere have recently been extensively studied both theoretically and experimentally, since these mechanisms have a large effect on the planning for frequency sharing, particularly between space and terrestrial systems.

Above about 10 GHz, and particularly in the millimetric band above 30 GHz, propagation is significantly limited by attenuation due to atmospheric gases, notably water-vapour and oxygen. In this part of the spectrum there are a number of resonance absorption lines - which may either be utilised or avoided, dependent on the application. However, the effect of rain and fog is very important. The test range at Chilbolton, together with detailed studies of the scattering from particles, have contributed to the present understanding.

8. THE FUTURE

100 years have seen dramatic changes in the available technology and in the needs for information. Perhaps, though, it is possible to look just a few years into the future and to the needs for propagation research. There does not at present seem to be any alternative to electromagnetic radiation for communication between places not connected by wires or fibres. Neither do there seem to be any major propagation modes which are not known at present, at least in general outline .

Thus propagation research will continue to be devoted to more precise characterisation and modelling of the medium. These should yield better prediction methods, with less statistical uncertainty, which may be applied to give greater utilisation of the spectrum. Much of the past research has been concerned with variations of signal strength, important for analogue systems. The rapidly increasing use of digital modulation will need new programmes of propagation studies designed to measure the important parameters for digital systems. Because of the demand for bandwidth, it seems unlikely that any part of the spectrum will be left fallow, although the usage will no doubt change as advances in technology and signal processing are brought to bear. There is no doubt that the small community of propagation researchers throughout the world will have important work to do for many years to come.

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